IIAR RESEARCH PROJECT WORK STATEMENT

Finite-element analysis of pressure vessels, piping, and their supports

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Prepared for:
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Executive Summary

This work statement proposes finite-element analysis (FEA) of example pressure vessels, towards the larger end of the types of refrigeration vessels sometimes installed outdoors, such as a 72-inch (1.8 m) diameter vertical receiver with these parameters varied: (A) shell length, (B) number and type of legs, (C) leg-to-vessel weld length and reinforcement plate, from none to a range of shapes, (D) amount and location of steel loss due to corrosion, including near nozzles and legs, and (E) installed locations with different earthquake, wind, or other external loads and outdoor temperatures. If worthwhile, examples of combined vessel, piping, and support systems could also be modeled. Outcomes: (1) base IIAR 6 acceptance criteria on a set of modeled loads, stresses, and strains after steel loss, and (2) potentially discover inexpensive design details that would improve safety margins in vessels, piping, and supports subjected to earthquakes, impacts, or wind.

1. Value to IIAR Members, Using the Results, and Overall Plan

1.1 Types of IIAR members who would benefit.

As described below, in section “1.3 Practical benefits expected”, the IIAR Member Categories who may benefit from the proposed research are:

- Contractor,
- Engineer (included with “contractors” below),
- End User I and II (called “owners” below), and
- Manufacturer (pressure-vessels manufacturers).

The adoption of the results would likely start where strong earthquakes, high winds, or low outdoor temperatures are more common, which includes the areas where the majority of the economic activity in North and South America take place. The likelihood of adoption would depend on the costs and benefits of FEA when applied to refrigeration systems, which the proposed research would help determine.

1.2 Dissemination of results.

Present a technical paper at the IIAR conference, published via the IIAR eLibrary, and also summarize the results in an IIAR *Condenser* article. Longer term, the results could be disseminated via their influence on future editions of the following IIAR publications:

- ANSI/IIAR 6 “Standard for Inspection, Testing, and Maintenance of Closed-Circuit Ammonia Refrigeration Systems” (IIAR 6),
- *The Refrigeration Piping Handbook*,
- *Principles and Practices of Mechanical Integrity Guidebook*, and
- *Guideline for Installing Insulation on Ammonia Refrigeration Systems*.

1.3 Practical benefits expected.

By soliciting proposals from FEA consultants -- who are experienced with FEA of pressure vessels, piping, and their supports (systems) for both the design of new systems and the analysis of existing corroded or otherwise damaged systems -- this research would gather information on the:
=> costs of FEA when applied to refrigeration systems.

By funding the best proposal, if a qualified consultant proposes to complete an adequate FEA scope at a cost the IIAR Research Committee deems reasonable, this research would gather information on the:
=> benefits of FEA when applied to refrigeration systems.

So, an outcome of the proposed research would be to demonstrate the costs and benefits of FEA applied to large, industrial, refrigeration systems. This would allow refrigeration-system owners and their contractors to better judge the cases when FEA may be practical and useful. These may include the:

- design of new systems in locations more likely to encounter powerful earthquakes, strong winds, or a combination of strong winds and cold outdoor temperatures, and
- assessment of existing systems with corrosion or other damage, particularly near where supports and vessels, supports and piping, or piping and vessels connect or contact.

The proposed research may discover inexpensive design details that would improve safety margins in vessels, piping, and their supports subjected to earthquakes, impacts, wind, or wind combined with cold outdoor temperatures. This may lead to guidance on design details for:

- the connections or contacts between vessels and their supports, such as welded joints and any reinforcement plates between vertical vessels and their legs,
- fastening foundations to supports, including vessel legs,
- vessel nozzles,
- supports, bracing, or flexible couplings for piping near its connections to equipment -- such as compressors, condensers, pumps, or vessels -- that may move differently from piping when subjected to dynamic horizontal or vertical acceleration or forces -- such as from earthquakes or wind, and
- piping supports in general, including for insulated piping.

Additional practical benefits are described below, in section “1.4 Application to IIAR publications”.

1.4 Application to IIAR publications.

1.4.1 IIAR 6 acceptance criteria.

IIAR 6-2019, section 10.1.1, calls for wall-thickness measurements, where corrosion that "is suspected to have materially reduced" a pressure vessel's wall thickness has been observed. And, it provides acceptance criteria for deciding what to do based on these wall-thickness measurements.

Regarding vessels and their supports, the proposed research would allow IIAR to:
=> base acceptance criteria in IIAR 6, section 10.1.1, on a set of FEA models of loads, stresses, and strains after steel loss.

Regarding piping and their supports, if worthwhile, based on the vessel results, examples of combined vessel, piping, and support systems -- or simpler combinations thereof, such as piping and supports -- could also be modeled. This would allow owners (including End User I and II members of IIAR) to:
=> base their "owner's established acceptance criteria" for piping, called for by IIAR 6-2019, section 11.1.1.3, on this additional set of FEA models.

1.4.2 Guidebooks and Handbooks.

If justified by the results and costs of the proposed research, the following could be updated.

The Refrigeration Piping Handbook could be updated to include:

- guidance on when FEA may be practical and useful and
- any discovered inexpensive design details that would improve safety margins -- see "1.2 Practical benefits expected" above. These design details should cover insulation where applicable, such as any added details on insulated pipes near their supports or their connections to vessels.

IIAR's *Guideline for Installing Insulation on Ammonia Refrigeration Systems* could be updated, if needed, with references to any design details affecting insulation that are added to *The Refrigeration Piping Handbook*.

IIAR's *Principles and Practices of Mechanical Integrity Guidebook* could be updated to include:

- guidance on when FEA may be practical and useful for assessing corroded or damaged pressure vessels, piping, and their supports, and
- short descriptions of the cases modeled via FEA, during the proposed research, with references to the published IIAR technical paper, so that any applicable modeled cases could inform decision-making about any actual similar future situations, including whether to make additional measurements or complete addition analysis.

1.4.3 IIAR 2 and compliance with the ASME codes that it references.

The proposed research is not expected to influence future editions of ANSI/IIAR 2 "Standard for Design of Safe Closed-Circuit Ammonia Refrigeration Systems" (IIAR 2). It may assist refrigeration-system owners and their contractors with designing for any applicable earthquake, impact, and wind loads per the American Society of Mechanical Engineers (ASME) vessel and piping codes that IIAR 2 has referenced. These ASME code requirements and their history are summarized below, in section "2. Background and State of the Art".

1.5 Overall plan and potential follow-up research.

A phased approach is proposed here, with the following steps.

1. **Advisory panel**. Assemble an advisory panel for the proposed research, which could be a subcommittee of the IIAR Research Committee, potentially augmented by IIAR staff and by others interested, such as some refrigeration-system owners, their contractors, or pressure-vessel manufacturers.
2. **Survey on unpublished FEA studies**. The advisory panel informally surveys refrigeration-system owners, contractors, and vessel manufacturers about any unpublished FEA models or results they may be willing to share with it. Modify the next steps based on anything received.
3. **Review FEA Scope 1, vertical vessel**. The advisory panel reviews and if needed modifies cases to be modeled via FEA in a first study scope, divided into three phases (Scope 1, Phases 1 to 3). These are described below, in section “4. Technical Approach”.
4. **Request Scope 1 proposals**. The advisory panel requests proposals from FEA consultants experienced with pressure vessels, piping, and their supports, such as Becht Engineering (becht.com), Paulin Research Group (paulin.com), Quest Integrity (questintegrity.com), or others.
5. **Review Scope 1 proposals**. The advisory panel assesses if one or more qualified consultants propose to complete an adequate FEA scope at a reasonable cost and makes recommendations to the IIAR Research Committee.
6. **Review Scope 1 results in phases, adjust future phases if needed**. If the IIAR Research Committee awards a contract to a consultant, after the consultant completes each phase of Scope 1, the advisory panel reviews its results and any recommendations for modifying subsequent phases, and it makes recommendations about the next phase to the IIAR Research Committee, who may authorize the consultant to proceed with the next, possibly modified, phase.
7. **Potential collaborators for additional scopes**. The advisory panel could consider collaborating with other organizations -- such as those representing agricultural ammonia, propane, and pressure-vessel manufacturers and distributors, for additional scopes because they would assess cases of more general relevance, like saddle supports for horizontal vessels, vessel-to-piping connections (near nozzles), and piping supports. Scope 1 focuses on a type and size of vertical vessel, with 3 or 4 welded legs, that is more unique to large refrigeration systems.
8. **Consider additional scopes**. The advisory panel assesses if it should request proposals for completing additional scopes, based on the costs and results of Scope 1. If so, the advisory panel makes recommendations on the details of subsequent scopes to the IIAR Research Committee. Preliminary possibilities for additional scopes, covering piping and piping supports, in addition to vessels and their supports, are also described below in section “4. Technical Approach”.

2. Background and State of the Art

Is it reasonable for the public to expect that pressure vessels, piping, and their supports can handle conditions easily foreseeable to occur in the locations where they are installed -- such as, where applicable, low outdoor temperatures, high winds, or earthquakes? And if this is now reasonable, how should engineers and organizations that design, manufacturer, install, own, and maintain pressure vessels, piping, and their supports, such as large refrigeration systems, go about ensuring this with a reasonable safety margin? Have our calculations about what is reasonable, based on cost and practicality, changed over time as the computing power and input information needed for numerical modeling, such as FEA, have become cheaper? This input information includes:

- three-dimensional (3D) digital models of vessels and piping, which are now routinely generated during design (almost always for vessels, often for piping, but less frequently for their supports), and
- consensus design values for earthquake ground acceleration versus period spectra as well as wind, snow, and ice loads, all of which are now freely available for all locations in the USA via the online ASCE 7 Hazard Tool, maintained by the American Society of Civil Engineers (ASCE).

The 1943 edition of the ASME Boiler Construction Code, Section VIII, Rules for Construction of Unfired Pressure Vessels, did not include an explicit requirement to design for wind and earthquake loads. It did have some rules for low metal temperatures. Its forward claimed that its “rules have been formulated to afford reasonably certain protection of life and property and to provide a margin for deterioration in service so as to give a reasonably long, safe period of usefulness.” It also warned, “The Code does not contain rules to cover all details of design and construction. Where complete details are not given, it is intended that the manufacturer, subject to the approval of the authorized inspector, shall provide details of design and construction which will be as safe as otherwise provided by the rules in the Code.”

In 1955, the ASME published “The Design of Vertical Pressure Vessels Subjected to Applied Forces”, a paper by E. O. Bergman, in which he discussed earthquake, piping, and wind loads and wrote that “Pressure-vessel codes do not give design methods except for [relatively simple cases...] The designer must apply engineering principles when he deals with more complicated structures and loading systems. [...] The codes furnish the designer with a list of approved materials and the maximum stress values in tension permitted over their usable range of temperatures. [...] The code requires that [the designer] shall provide details of construction that will be as safe as those provided by the rules of the code [...] This paper discusses some problems of design of cylindrical pressure vessels that have their axes vertical and are subjected to applied forces in addition to internal or external pressure. The vertical forces considered are the weight of the vessel and its contents and the weight of any attachments to the vessel. The horizontal forces include wind pressures, seismic forces, and piping thrusts.” The codes this paper referenced were the 1952 edition of the ASME Boiler and Pressure Vessel Code, Section VIII, Rules for Construction of Unfired Pressure Vessels, and the 1951 (fifth) edition of the API-ASME Code for the Design, Construction, Inspection, and Repair of Unfired Pressure Vessels for Petroleum Liquids and Gases.

(1) [1955] E. O. Bergman, *Trans. ASME*, August 1955, Volume 77, Issue 6, pages 863-866. https://doi.org/10.1115/1.4014519

Since before the 1971 edition, considering loads from earthquakes, impacts (such as fluid shock), supports, wind, and several other sources has been specifically required by Subpart UG-22, Loadings, in Part UG, General Requirements for All Methods of Construction and All Materials, of the model code that by then was titled the ASME Boiler and Pressure Vessel Code, Section VIII, Rules for Construction of Pressure Vessels, Division 1 (ASME VIII-1).

The 2019 edition of ASME VIII-1 included a reference, in Table U-3, to the ASCE and Structural Engineering Institute (SEI) Standard ASCE/SEI 7 “Minimum Design Loads and Associated Criteria for Buildings and Other Structures” (ASCE 7) as a potential source for applicable wind and earthquake loads. Its nonmandatory Forms U-DR-1 and U-DR-2, “User’s Design Requirements […]”, provide one method for a vessel user to communicate to its manufacturer applicable earthquake (seismic) and wind design conditions, when ordering a vessel.

For piping, considering earthquake, impact, and wind loads has similarly been required since before the 2001 edition (probably since the 1960s) of the model code titled Section B31.5, Refrigeration Piping and Heat Transfer Components, ASME Code for Pressure Piping, B31 (ASME B31.5). By the 2013 edition of ASME B31.5, it referenced ASCE 7 for wind and earthquake loads.

Many cities, states, and other jurisdictions have incorporated some or all of various editions of the above ASME model codes into their laws since the early 1900s, and in 1919 The National Board of Boiler and Pressure Vessel Inspectors (NBBI) was organized, in part to promote more uniform enforcement of ASME codes in the USA. Since the 1970s, the IIAR has called for compliance with ASME VIII-1 and ASME B31.5 in their standard for new installations, IIAR 2.

For installations in the USA and many other countries, refrigeration pressure-vessel manufacturers typically use design-by-rule methods from ASME VIII-1, for vessels and nozzles, and the American Institute of Steel Construction (AISC), for supports, often implemented by computer programs (software) such as Codeware Inc.’s COMPRESS or Hexagon AB’s PV Elite. For earthquake and wind vibration analyses, these software packages sometimes augment the design-by-rule methods’ fairly simple math equations (closed-form expressions) with “lumped mass” numerical methods that simplify vessels and supports, cannot simulate the details of nozzle and support connections to vessels, cannot simulate buckling, and may lead to inaccuracies, particularly if the natural frequencies of the second or higher mode shapes need to be estimated. To address such cases, these software packages allow data exchange with 3D modeling and FEA software packages.

FEA is common for the design of metal or composite components and structures, including for pressure vessels, piping, and their supports. These supports may include everything from a pipe hanger or rack, the roofs, floors, buildings or other structures that support these hangers or racks, all the way down to and including their foundations. For example, see the definitions of “support” in standards IIAR 1-2022 and IIAR 6-2019.

FEA’s accuracy in estimating strain in pressure vessels, piping, buildings, and other structures is well established, if properly done. Recent papers comparing FEA results to strain and displacement measurements on actual steel pressure vessels subjected to known loadings and stresses, in laboratory settings, include [references numbered sequentially]:

(2) [2023] “Ultimate strength of cylindrical shells with corrosion damage: Comparing theoretical and experimental results”, Yongmei Zhu, Xialei He, Wei Liu, Wei Guan, Min Zhao, Jian Zhang, *International Journal of Pressure Vessels and Piping*, Volume 202, April 2023 (published online 2023-01-07), page 104888. https://doi.org/10.1016/j.ijpvp.2023.104888
* Studied buckling due to external pressure on small, 4 inch (100 mm) inner diameter by 7 inch (170 mm), cylindrical shells with flat heads, no supports, and made from 304 stainless steel.
* “Very good correlation between the numerical buckling load considering real corrosion defects and the experimental buckling load was obtained (within ±8.2%).”

(3) [2009] “A comparative study of usefulness for pad reinforcement in cylindrical vessels under external load on nozzle”, J. Fang, Q. H. Tang, Z. F. Sang, *International Journal of Pressure Vessels and Piping*, Volume 86, Issue 4, April 2009, pages 273-279.
https://doi.org/10.1016/j.ijpvp.2008.09.010
* FEA and test results agreed to within 13% in all cases studies, for both strain and displacement, and some of the discrepancy may have resulted from measurement error.

Most FEA results are proprietary and are never published.

An informal survey of refrigeration-system owners, contractors, and vessel manufacturers about any unpublished FEA studies that they may be willing to share with the IIAR Research Committee is an initial step of the proposed research; see section “1.5 Overall plan and potential follow-up research” above. However, proprietary and other concerns may limit the willingness of owners or manufacturers to share FEA models or results for vessels in current service or offered for sale in competitive markets.

Still, the small published portion of the vast number of FEA studies completed in recent decades now includes many papers, even just for pressure vessels and piping. Jaroslav Mackerle, Linköping University, Sweden, published several bibliographies of “finite elements in the analysis of pressure vessels and piping…” documenting a few more than 4,000 journal papers (peer-reviewed), conference proceedings, and theses dissertations from 1976 to 2004. A gray literature of FEA results has also been published outside of science and engineering journals, such as summary case studies on the websites of engineering and architecture consultants.

Unfortunately, searches via Google, Google Scholar, publisher and Scopus “cited by” lists, and by tracing references in somewhat relevant papers found no published studies relevant to a common style of refrigeration vessel in the last 25 years:

- vertical, supported on three or four legs made from steel angles, and potentially loaded by earthquakes or wind, in addition to internal pressure and the weight of the vessel and its contents.

The most relevant publications found about vessel supports (the focus of proposed Scope 1 Phase 1) were:

(4) [2021] “Study of Effect of Angle of Contact and Angle of Extension of Wear Plate on Maximum Stress Induced in Horizontal Pressure Vessel”, Aniruddha Nayak, Pravin Singru, Chapter in: Y. V. D. Rao, C. Amarnath, S. P. Regalla, A. Javed, K. K. Singh (editors) *Advances in Industrial Machines and Mechanisms,* Springer, Singapore.
https://doi.org/10.1007/978-981-16-1769-0_46
* Abstract: "Horizontal Pressure Vessels are supported by two saddle supports near the ends. There is a local stress concentration in the vessel near the saddle horn of the saddle support. The parameters of a saddle support that can be changed are the angle of contact of the saddle, the width of saddle, the width of wear plate, and extension of the wear plate over the saddle horn. These parameters directly govern the values and location of maximum stress in the vessel. The aim of this study is to perform FEA analysis and find the effects of different configurations of the saddle and its effect on the maximum stress in the vessel and thus find the most optimum configuration of the saddle to pass the ASME requirements while keeping the material costs at the minimum."

(5) [2019] “A Case Study of Structural Industrial Pressure Vessel Under Wind Load”, Sanjida Haque, Seth Nowak, Robyn Callaghan, Ashim Mukerjee, Rahul Prasad, Mosfequr Rahman, Aniruddha Mitra, Proceeding of the 2019 Conference for Industry and Education Collaboration, https://peer.asee.org/a-case-study-of-structural-industrial-pressure-vessel-under-wind-load.pdf
* Vertical vessel, 60 inch (1.5 m) outer diameter, on three W8x31 ASTM A36 vertical steel legs.
* Simulated vessel in 30 and 120 mph (48 and 193 km/h) winds via FEA. No earthquake simulations.
* "Air flowing past a body at a certain velocity will create vortices at the rear of that body initializing an oscillating flow. This oscillating flow depends on the size, shape and structure of the blunt body obstructing the flow of air. The oscillating flow is known as vortex shedding and its frequency is known as the vortex shedding frequency. A resonating condition may arise resulting in significant damage as the vortex shedding frequency approaches the natural frequency of the structure."

(6) [2012] “Vessel Supports”, Gavin Towler, Ray K. Sinnott, section 14.9 of *Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design*, Amsterdam, Netherlands: Elsevier, 2012, 2nd Edition.
https://www.sciencedirect.com/book/9780080966595/chemical-engineering-design
* "Supports will impose localized loads on the vessel wall, and the design must be checked to ensure that the resulting stress concentrations are below the maximum allowable design stress." (page 598)
* FEA not covered.

(7) [2012] “FEA based analysis for determining structural stability of leg support system for pressure vessel”, S. A. Pawar, P. S. Kachare, International Conference on Mechanical and Industrial Engineering (ICMIE), ISBN: 978-93-81693-74-2, Pune, India.
https://www.researchgate.net/publication/301820650_FEA_based_analysis_for_determining_structural_stability_of_leg_support_system_for_pressure_vessel
* FEA results: 4-leg symmetrical-support system was more stable than 6-leg unsymmetrical support system.
* Limited usefulness because cross section of legs was not described.

(8) [2012-2014] A series of poorly documented papers were published by the free *International Journal of Engineering Research & Technology* on an inclined vessel and also vertical vessels with unsymmetrical leg layouts to accommodate equipment under the vessel. They are not useful due to inadequate details on both the systems studied and the results.

(9) [1981] “A method for maximizing support leg stress in a pressure vessel mounted on four legs subject to moment and lateral loading”, Krishna P. Singh, *International Journal of Pressure Vessels and Piping*, Volume 9, Issue 1, January 1981, pages 11-25.
https://doi.org/10.1016/0308-0161(81)90033-8
* Abstract: "Pressure vessels mounted on four-leg type supports form a non-isotopic support system with respect to lateral loads or overturning moments. Several loadings -- for example, horizontal earthquake motions and wind loads -- do not have a predefined direction of action. Structural safety analysis requires the determination of the most vulnerable direction of loading for the structure. Closed-form expressions for these loadings under certain conditions are derived in this paper. The importance of 'optimality' with respect to the developed stress in the support is illustrated via a numerical example."
* FEA not covered.

An annotated bibliography of the studies reviewed, which may be updated periodically, will be posted by March 6, 2023, at: https://factplusfancy.com/fea

3. Advancement to the State of the Art

As described above, in sections 1.3 and 1.4, the proposed research:

- may discover inexpensive design details that would improve safety margins in pressure vessels, piping, and their supports for large refrigeration systems and
- would allow basing IIAR 6 acceptance criteria on a set of FEA models of loads, stresses, and strains after steel loss.

The IIAR 6-2019, section 10.1.1, acceptance criteria for pressure vessels were based on the 2017 National Board Inspection Code (NBIC) for liquid-ammonia vessels. These NBIC acceptance criteria were first adopted in 2011. In an October and November 2022 email exchange, I asked Luis Ponce, Manager of Technical Services at NBBI, about the difference between the ammonia and liquefied-petroleum gas (LPG) vessel acceptance criteria in the 2011 to 2021 NBIC editions, which for ammonia have only a 75% of required thickness minimum requirement, whereas for LPG they have an additional 90% of required thickness averaged over 10-inches requirement. Mr. Ponce looped in Jonathan Ellis, the NBIC Code Coordinator at NBBI, but they did not find an explanation at the time. No minutes were found from the two years prior to the 2011 adoption of 75% of required thickness for liquid-ammonia vessels, and the documents found for the 2019 adoption of 75% of required thickness for compressed-air vessels did not provide a rationale. Mr. Ponce suggested that I submit a NBIC code-change request, which I did on January 17, 2023, when I also forwarded a copy of this code-change request to Eric Smith and Tony Lundell, IIAR, via email. For simplicity, and without the resources to do FEA on a wide range of cases, I based this code-change request on the conservative acceptance criteria in API 579-1/ASME FFS-1, Fitness-For-Service, 2021 edition (ASME FFS-1), Part 3 Level 1 (brittle fracture) as well as Part 4 Level 2 and Part 5 Level 1 (wall thinning). The proposed research would likely support less conservative acceptance criteria, compared to what was in this January 17, 2023, code-change request, due to its resemblance to applicable ASME FFS-1 Level 3 analyses.

The proposed research resembles both:

- the design by analysis FEA methods in Division 2 of Section VIII of the ASME Boiler and Pressure Vessel Code (ASME VIII-2) and
- ASME FFS-1 Annex 2D (FEA stress analysis) and Level 3 analyses under Parts 3, 4, 5, and 6 (covering brittle fracture, general metal loss, local metal loss, and pitting).

So, the proposed research would not advance the general state of the art for FEA of pressure vessels, piping, and their supports. Instead, it would demonstrate the costs and benefits of applying well established FEA methods to refrigeration systems, including their supports, thereby clearing a trail for owners and contractors to use FEA for refrigeration systems, when appropriate. The unexpected pitfalls encountered and the methods used to surmount them, in completing the proposed research, would reduce the time and effort that owners and contractors would have to put into their initial FEA studies, for new designs or for existing systems with corrosion or other damage.

The costs of FEA may continue to decline in the years to come, making it more practical to apply to refrigeration systems.

4. Technical Approach

The following request-for-proposal wording would apply to all scopes.

Complete FEA -- consistent with ASME FFS-1 Annex 2D, ASME VIII-2 design-by-analysis methods, and also AISC, American Concrete Institute (ACI), or other relevant structural analysis methods for supports and foundations -- of the pressure vessels, piping, and/or supports described in the applicable scope in Table 1 to assess their safety margins for protection against all relevant failure modes, including:

- brittle fracture, at a reasonable lowest outdoor temperature, at the locations specified in Table 1 (because low internal temperatures are associated with low internal pressures, in refrigeration, brittle fracture due to low outdoor temperatures reasonably combined with ASCE 7 loads shall be assessed instead),
- plastic collapse,
- local failure (such as based on peak-strain values),
- buckling collapse, and
- if applicable, fatigue damage from any cyclic ASCE 7 loads. Ammonia-refrigeration temperature and pressure changes -- from defrosting, shutdowns, etc. -- are rarely, if ever, large enough to causes steel fatigue, even over 50 years.

Include the following load categories in the FEA modeling, combined per ASME FFS-1 guidance (load factors to reasonably evaluate load combinations):

- internal pressure,
- weight of the liquid ammonia at the fill heights specified in Table 1,
- weight of the vessel and any insulation systems, and
- ASCE 7 loads -- earthquake, wind (including vortex-shedding vibrations), snow, ice, etc. -- at the geographic locations specified in Table 1.

Include modal and vibration analyses as needed to assess safety margins against the above failure modes consistent with the above-referenced codes and standards.

The tables below provide additional details, for each scope and phase. The steel loss geometries in the tables below are intentionally simple, to facilitate interpretation and to reduce FEA costs.

> Note to IIAR Research Committee: If this research progresses to a request for proposal, sketches of the equipment described in the tables below could be prepared.

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Table 1, Page 1 of 3. Scope 1 Phase 1 proposed cases for FEA.

Parameter Description	**Parameter value**
Vessel orientation	Vertical
Outer diameter	72 inch (1,829 mm)
Heads type	2 to 1 elliptical
Each head, length of elliptical portion	18 inch (457.2 mm)
Each head, straight-flange length	2 inch (50.8 mm)
Each head, total length	20 inch (508 mm)
Shell length	168 inch (4,268 mm)
Vessel overall length	208 inch (5,283 mm)
Maximum Allowable Working Pressure (MAWP), the design pressure. (Scope 1 Phase 2 would evaluate a higher MAWP, needed for some geographic locations.)	250 PSI at 300ºF (1.72 MPa at 149 C)
Minimum Design Metal Temperature (MDMT), dual stamped.	-20ºF at 250 PSI (-29 C at 1.72 MPa) -50ºF at 100 PSI (-46 C at 0.69 MPa)
Fill height	Vessel 80% full by volume.
Shell and heads material	SA516 Grade 70 (not normalized)
Shell thickness as built from 5/8-inch plate with no undertolerance reduction.	0.625 inch (15.88 mm)
Heads minimum thickness as built, after hot forming from 5/8-inch plate.	0.562 inch (14.27 mm)
Efficiency (E) of longitudinal shell weld (2019 ASME VIII-1, Joint Category A, Table UW-12 Type 1 weld, examination: spot)	0.85
Efficiency of girth and head-to-shell welds (2019 ASME VIII-1, Joint Category B, Table UW-12 Type 2 weld, examination: none)	0.65
Post-weld heat treatment (PWHT)	45 minutes at 1150°F (621 C) Not required by ASME VIII-1.

Table 1, Page 2 of 3. Scope 1 Phase 1 proposed cases for FEA.

Parameter Description	**Parameter value**
Shell required thickness (t) for internal pressure per 2019 ASME VIII-1, UG-27, Equation (1): t = PR/(SE-0.6P), with allowable stress (S) of 20,000 PSI, P = 250 PSI, inner radius (R) = 35.375 inch, and E = 0.85. As typical, circumferential/hoop stress (acting on the longitudinal seam welds) gives the thickest value.	0.525 inch (13.3 mm)
Head required thickness (t) for internal pressure, per 2019 ASME VIII-1, UG-32(c), Equation (1): t = PD/(2SE-0.2P), with no welds in elliptical portion of head (E = 1), a maximum head inner diameter (D) of 70.875 inch, and both S and P as above.	0.444 inch (11.3 mm)
MDMT from Figure UCS-66 (2019 ASME VIII-1), Curve B (SA516-70 not normalized), 0.625 inch (15.88 mm)	5ºF (-15 C)
Reduction of Figure UCS-66 MDMT allowed for PWHT of P1 materials, such as SA516-70, when PWHT is not required by ASME VIII-1, per UCS-68(c). Same result as ASME FFS-1, 2021, Equation 3.1.	30ºF reduction (17 C reduction)
Reduction of Figure UCS-66 MDMT allowed by Figure UCS-66.1 with no steel loss from nominal (and no corrosion allowance) at 250 PSI.	~28ºF reduction (~15.6 C reduction)
Reduction of Figure UCS-66 MDMT allowed by Figure UCS-66.1 with 30% steel loss from nominal corrosion allowance at 100 PSI.	~90ºF reduction (~50 C reduction)
Legs, number	3 (120º evenly spaced around vessel.)
Legs, length	50 inch (1270 mm)
Legs, material and cross section	SA36 L6x6x1/2 inch (152.4 x 152.4 x 12.7 mm) steel angle (90º)
Legs to vessel welded joints	Corner-flange weld on outside of angle. Detail more if needed.
Legs to vessel welded joints length	13 inch (330.2 mm) overall, including 11.5 inch (292 mm) on shell and 1.5 (38 mm) inch on the bottom head's straight flange, with a 1-inch (25.4 mm) diameter semi-circular notch in each flange of the steel angle to clear the head-to-shell weld.
Bottom of vessel to top of foot plates distance	18 inch (457 mm)
Foot plates, material	SA516 Grade 70

Table 1, Page 3 of 3. Scope 1 Phase 1 proposed cases for FEA.

Parameter Description	**Parameter value**
Foot plates, dimensions	10 x 10 x 0.5 inch (254 x 254 x 12.7 mm)
Legs to foot plates welded joints	0.25 inch (6.4 mm) fillet weld on all sides of angle.
Boundary condition	Fixed foot plate
Installed location, for determining ASCE 7 loads and the design outdoor-temperature range.	Three cases: Long Beach, California Pensacola, Florida St. Cloud, Minnesota
Head straight flanges length. Assess if they allow the head side of a head-to-shell weld to be treated like a shell-to-shell circumferential/girth weld, with easier fitness-for-service requirements per ASME FFS-1, 2021 edition.	Increase straight flange length, if needed to avoid stress concentrations near head-to-shell welds and ASME FFS-1 classification of this welded joint as a structural discontinuity, such as Component Type B or C.

Table 2. Scope 1 potential Phase 2 cases for FEA.

Parameter Description	**Parameter value**
Vessel-wall steel loss due to exterior corrosion, followed by blend grinding. Consider brittle-fracture prevention and MDMT calculations, in the FEA and also when interpreting the meaning of “ASME VIII-1 required thickness”.	To 75% of the ASME VIII-1 required thickness of the vessel wall within 3 inches (76 mm) from each leg-to-shell joint, linearly returning to the original/nominal thickness over 1-inch (25 mm).
Maximum Allowable Working Pressure (MAWP), the design pressure. Increasing to 300 PSI (2 MPa) would require either full radiographic or ultrasonic examination of the longitudinal seam weld (E = 1) or using 3/4-inch (19.1 mm) plate.	300 PSI at 300ºF (2.07 MPa at 149 C)
Shell length and fill height.	Increase or decrease based on Phase 1 results.
Legs, number	4 (90º evenly spaced around vessel.)
Legs, length overall Legs to vessel welded joints length	Assess a longer optimal length, if worthwhile at one or more geographic location.
Reinforcement plate between legs and vessel	Assess optimal dimensions and weld type and size, if worthwhile at one or more geographic location.

Table 3. Scope 1 potential Phase 3 cases for FEA.

Parameter Description	**Parameter value**
Leg steel loss, one leg only	To 75% of original/nominal thickness in first 3 inches (76 mm) above its foot plate, linearly returning to the original/nominal thickness over 1-inch (25 mm).
Leg steel loss	Assess other scenarios.
Vessel-wall steel loss due to exterior corrosion	Assess other scenarios.
Legs, material and cross section	Assess any benefits of using wide-flange beams, such as SA36 W6x25, W8x35, or a more optimal shape, if worthwhile at one or more geographic location.
Post-weld heat treatment (PWHT) and normalized steel.	Evaluate brittle-fracture prevention after vessel-wall steel loss to below nominal near legs without PWHT. Also, assess costs and benefits of using normalized steel, SA516-70N, to prevent brittle fracture, either with or without PWHT.

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Table 4, Page 1 of 2. Potential additional scopes, if worthwhile.

Parameter Description	**Parameter value**
Vessel material	Assess using stainless steel, lowest cost grade that improves safety factors, if any.
Vessel, piping, and support systems. Add three typically sized and located nozzles, made from SA106, Grade B, Schedule 80 pipe, to the Scope 1 vessel -- such as: * one 6-inch (152 mm) nozzle, centered 7 inches (178 mm) below the upper head-to-shell weld, for condenser-drain (CD) piping, * one 4-inch (102 mm) nozzle, centered 6 inches (152 mm) above the lower head-to-shell weld, for high-pressure liquid (HPL) piping, and * one 4-inch (102 mm) nozzle, in the center of the upper head, for equalization (EQ) piping. Also add A106, Grade B, Schedule 40 piping running from the pipe nozzles to pipe supports on a roof: * foot plate to roof piping (bottom of both): 30 feet (9 m), * edge of vessel to 1st support on roof: 4 feet (1.2 m), * edge of vessel to 2nd support on roof: 18 feet (5.5 m), * edge of vessel to 3rd support on roof: 32 feet (10 m), * piping fixed at 3rd support (boundary condition), * the CD piping runs horizontally 2 feet (0.6 m) and includes an angle-pattern globe valve to turn upward. * the EQ piping includes a Y-pattern globe valve 1 foot (0.3 m) from the nozzle weld, and * the HPL piping runs horizontally, 5 feet (1.5 m) from the vessel and there includes a Y-pattern globe valve, a solenoid valve, an angle pattern globe valve to turn upward, and also two tees connecting 4-inch (102 mm) bypass piping (around all three previous valves), with an angle-pattern globe valve connecting the horizontal with the vertical portions of the bypass piping.	Compare Cases A and B below. Case A: * Supports made from 4x4 inch (51x51 mm) A36 square tubing. * Round pipe rests directly on flat support without anything securing it to the support, except fixed at the 3rd support (boundary condition). * No supports or bracing between vessel and the 1st roof support. Case B: * Optimize supports and any needed bracing, including increasing the contact area between the pipe and support, if worthwhile at one or more geographic location.
Piping and support systems.	Compare Cases A and B above, for a set of horizontal pipe runs. Also compare insulated to bare (painted only) pipes.
Steel loss from all of above.	Select cases based on prior phases.

Table 4, Page 2 of 2. Potential additional scopes, if worthwhile.

Parameter Description	**Parameter value**
Anchoring foot plates to reinforced-concrete foundations	Assess stresses in foot plates, bolts, nuts, and anchors in the foundations when subject to ASCE 7 loads. Compare sizes and methods, and optimize.
Saddle supports See Nayak et al. (2021), reference (4) above.	Compare: (A) saddle is welded to vessel versus (B) vessel rests on saddle with various types of wear material in between, for a range of sizes. Optimize saddle shape and wear materials and sizes to minimize stress, including at the saddle horn.
Pitting combined with local corrosion, without any remediation via blend grinding.	Assess stress concentrations.
Flexible couplings between piping and equipment -- such as compressors, condensers, pumps, or vessels -- that may move differently from piping when subjected to dynamic horizontal or vertical acceleration or forces.	Assess if worthwhile, at various geographic locations.

5. Deliverables

After completing each phase, the consultant shall post, in a secure folder accessible to the IIAR advisory panel for this research:

1. a document (pdf) with a short narrative summary and images of results marked up to show key findings,
2. recommendations on modifications to the cases to be modeled for the next phase, if any,
3. digital copies of all 3D, FEA, and any other models and output developed by the consultant to complete the phase, in the standard format of the software used to produce them plus, if requested, up to one additional format, and
4. an invoice detailing the consultant's costs incurred for the phase.

All deliverables under this Agreement and any voluntary technical articles shall be prepared using dual units, such as rational inch-pound with equivalent International System (SI) units shown parenthetically. SI usage shall be in accordance with IEEE/ASTM Standard SI-10.

The above deliverables are necessary, *but not sufficient*, to monitor a research project. The advisory panel for this research and the IIAR Research Committee are responsible for reviewing the consultant's intermediate results, to ensure that the methods used and results obtained will be valid and adequately substantiated to be labeled as “IIAR-approved findings.” Proper oversight cannot wait until the final report, when most of the budget has already been expended.

After completing as many scopes and phases as requested, per the services agreement between IIAR and the consultant, the consultant shall draft an IIAR Technical Paper, of similar length and complexity as

2020 IIAR Technical Paper 1, T484, “CFD Simulation of NH 3 Release and Detection in Refrigerated Spaces”, and shall collaborate with the IIAR advisory panel on this, as joint authors.

> Note to IIAR Research Committee: the above deliverables are simplified compared to the generic IIAR requirements, to reduce costs and because the above Item 3, digital copies of all 3D and FEA models and output, would provide details similar to what the generic IIAR requirements call for, for other types of projects.

6. Level of Effort and Timing

The FEA modeling for each phase may only take a few days, with some additional effort to prepare a report to communicate the results. However, allowing two months for each phase may lead to lower costs, by allowing the consultant to complete this effort during slow periods in their schedule.

To accurately estimate costs for the proposed research, consultant proposals, based on a request for proposals, would need to be obtained.

An FEA consultant’s informal estimate, based on a scope similar to Scope 1, in Tables 1, 2, and 3 above, was:

- $30,000 to $75,000.